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Interglacial Extension of the Boreal Forest Limit in the Noatak Valley, Northwest Alaska: Evidence from an Exhumed River-Cut Bluff and Debris Apron

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Abstract

Numerous exposures of Pleistocene sediments occur in the Noatak basin, which extends for 130 km along the Noatak River in northwestern Alaska. Nk-37, an extensive bluff exposure near the west end of the basin, contains a record of at least three glacial advances separated by interglacial and interstadial deposits. An ancient river-cut bluff and associated debris apron is exposed in profile through the central part of Nk-37. The debris apron contains a rich biotic record and represents part of an interglaciation that is probably assignable to marine-isotope stage 5. Pollen spectra from the lower part of the debris apron closely resemble modern samples taken from the Noatak floodplain in spruce gallery forest, and macrofossils of spruce are also present at this level. Fossil bark beetles and carpenter ants occur higher in the debris apron. Mutual Climatic Range (MCR) estimates from the fossil beetles suggest temperatures similar to or warmer than today. Together, these fossils indicate the presence of an interglacial spruce forest in the western part of the Noatak Basin, which lies about 80 km upstream of the modern limit of spruce forest.

Introduction

One of the most important potential effects of future climate warming in the Arctic is the displacement of the limits of boreal forest. Not only would a change in boreal forest distribution lead to local and regional-scale changes in landscape and ecosystem processes, but a considerable impact on the climate system is predicted due to albedo-related modification of land-atmosphere feedback (Bonan et al., 1992; Foley et al., 1994; Pielke and Vidale, 1996). Thus, there is considerable current interest in evidence of past tree-line shifts and their probable causes.

The last interglaciation *sensu lato* (marine isotope stage 5 [MIS-5]) is of particular interest as a possible analogue for global warming. Evidence from the high northern latitudes indicates that one or more of its substages were warmer than the Holocene (LIGA Members, 1991). Sea level was higher (Hopkins, 1982), the Greenland ice was probably less extensive (Cuffey and Marshall, 2000), and in some regions plant and animal taxa expanded well beyond their Holocene ranges (e.g., Matthews et al., 1990). There are, however, few interglacial sites recording tree-line extensions, even in northern Alaska, where the limited Wisconsinan ice extent should have increased the potential for interglacial deposits to be preserved, compared with more intensely glaciated regions.

The northwestern limit of white spruce (*Picea glauca* [Moench] Voss) lies in the lower Noatak drainage (Fig. 1). In Alaska, northern tree lines appear to be at their greatest Holocene extent today (Anderson and Brubaker, 1994; Edwards et al., 2000). Scattered evidence suggests earlier extensions of the tree line, though few sites are well dated. Recent pollen studies at Ahaliorak Lake, north of the Brooks Range, suggest forested conditions during all or part of the last interglaciation (Brubaker et al., 1996). At Squirrel Lake, southwest of our study area, pollen data from the same period indicate extensive forest (rather than gallery forest) in the Squirrel River drainage (Berger and Anderson, 1994; P. Anderson, personal communication, 1999). Carter and Ager (1989) report both pollen and macrofossil evidence for *Picea* expansion beyond its current limits in northern Alaska during the late Pleistocene. Macrofossils and/or pollen from Cape Deceit (Matthews, 1974), Imuruk Lake (Colinvaux, 1964; Shackleton, 1982), and Cape Blossom (J. Brigham-Grette, personal communication, 1991) indicate the presence of spruce forest beyond its current limits on the Seward Peninsula and adjacent to Kotzebue Sound during one or more warm intervals in the mid Pleistocene.

The Noatak basin contains a rich depositional record of middle and late Quaternary age (Hamilton, 2001). Numerous bluffs along the Noatak River and its principal tributaries stand 20–85 m high and expose glacial and glaciolacustrine deposits interstratified with fluvial sediments. Glacial deposits are assignable to multiple advances of the middle and late Pleistocene; the fluvial sediments represent at least two major interglaciations, several interstadial episodes, and the Holocene interval. Interglacial deposits characteristically contain

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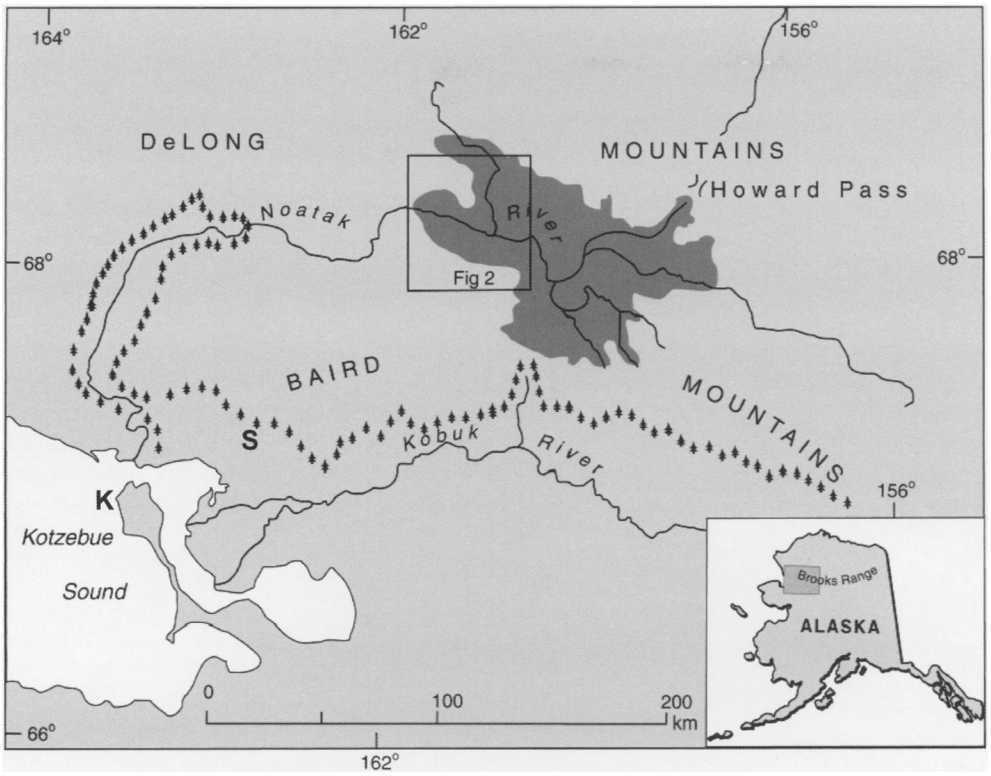

FIGURE 1. Location map showing Noatak Basin (darker shading). Current northward limit of spruce is indicated by tree symbols. K, Kotzebue; S, Squirrel Lake (Anderson, 1985). Modified from Hamilton (2001).

thick horizons of peat and/or organic-rich silt; pollen and insect assemblages indicate paleotemperatures as mild as or warmer than the present day (Elias et al., 1999b). In this paper, we present the stratigraphic and fossil record from the exposed profile of an ancient river-cut bluff face and associated debris apron, which probably corresponds with some part of the MIS-5 interglaciation. The sediments contain fossil evidence for the existence of spruce forest at least 80 km beyond its current position in the Noatak Valley.

The Study Area

The Noatak River, which originates in the central Brooks Range, flows westward between the DeLong and Baird Mountains; it then curves south and discharges into Kotzebue Sound (Fig. 1). About 110 km below its headwaters, the river valley broadens into the Noatak basin, a lowland up to 80 km wide that extends downvalley for 130 km with a valley-floor elevation of ca. 300–350 m a.s.l. The basin floor is underlain by permafrost, which generally is continuous beneath the basin and surrounding uplands (Ferrians, 1965; Brown et al., 1997). Much of the basin is characterized by low-shrub tundra and shrub-tussock tundra, the latter in moister areas. Major taxa are *Betula glandulosa* (shrub birch), *Salix* spp. (willow), and heaths. *Salix* shrubs occur along watercourses and on floodplains, and more exposed slopes support fell-field tundra. *Populus balsamifera* (balsam poplar) occurs in the western Noatak basin, and *Alnus crispa* (alder) shrubs are scattered throughout the basin. Although there are apparently suitable establishment sites on the floodplain in the Noatak basin, the present northwestern limit of white spruce occurs ca 80 km west and downstream from the basin, as gallery forest bordering the Noatak and its tributaries (Fig. 1).

The dynamic floodplain environment is associated with successional vegetation sequences. *Salix* and sometimes *Populus* occupy newly exposed alluvium during the early stages of succession. In the lower Noatak, *Picea* colonizes subsequently, if the substrate remains stable. On older terraces, as permafrost begins to influence the site the forest may thin out and become replaced by sedge meadows. On well-drained higher surfaces, forest is replaced by dry *Betula*-shrub tundra (M. E. E., personal observation, 1995).

The climate of northwest Alaska is characterized by long, cold winters and short, cool summers. Mean July and January temperatures at Kotzebue (Fig. 1), which is the nearest weather station to the study area with a long record, are ca. 12°C and ca. –20°C respectively; precipitation averages 230 mm, more than half falling in the summer and early fall (US Weather Service data). There are no permanent climate stations in the study area. To estimate climate conditions we use climate values extrapolated from climate stations onto a 25-km topographic grid (K. Anderson and others, unpublished North American gridded climate data set).

Using five grid squares with a mean elevation below 400 m a.s.l. (range 305–366 m), the interpolated values for the Noatak basin give slightly cooler summers (ca.11°C) and colder winters (ca. –24°C) than Kotzebue, and greater annual precipitation (ca. 338 mm). The same procedure applied to the lower Noatak valley (8 grid cells under 400 m, range 61–290 m) gives temperature means of 10.8 and –21.8°C and annual precipitation of 278 mm. The accuracy of these estimates is probably only moderate (K. Anderson, personal communication, 1999). For example, they cannot take into account regional topographic control of storm tracks and local "mountain weather," both of which contribute to variable local climates in the western Brooks Range (T. D. H., personal observation).

During Pleistocene glacial intervals, glaciers from the central Brooks Range extended into eastern and southern parts of the basin. A separate glacier complex formed in the De Long Mountains. Ice tongues from that source region flowed southeastward into the Noatak basin, damming the Noatak River and forming a succession of lakes collectively known as glacial lake Noatak (Hamilton, 1984a, 1984b, 2001; Hamilton and Van Etten, 1984). The more extensive glacial advances filled most of the basin with glacier ice and proglacial lakes; less extensive advances created narrower water bodies along valley centers (Hamilton, 2001). During periods of glacial retreat, the Noatak

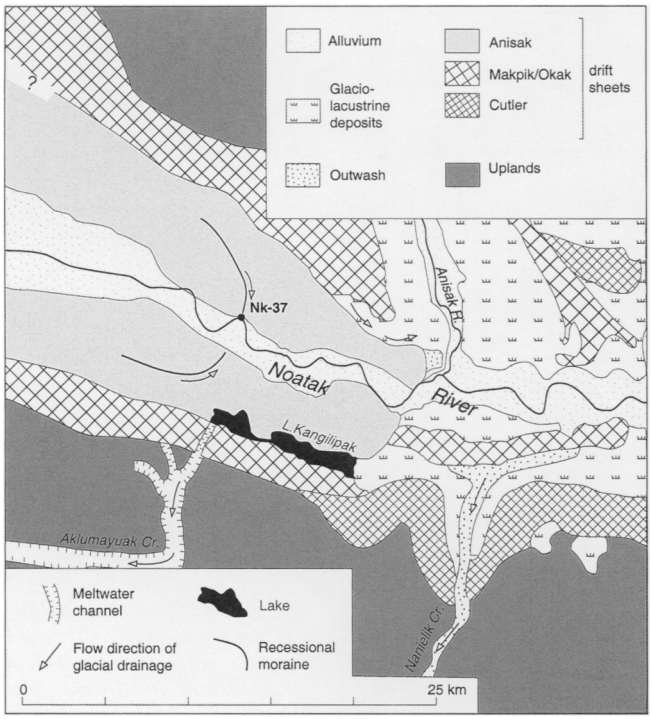

FIGURE 2. Location of Nk-37 in relation to glacial deposits in western Noatak basin. The Cutler glacial advance is believed to be of middle Pleistocene age; the Makpik/Okak and Anisak advances are younger than MIS-5e but beyond the range of radiocarbon dating. Modified from Hamilton (2001).

River system reassembled in its basin. The river cut down through stagnating glacier ice and glacial detritus, draining the glacial lake, and subsequently incised the glacial and glaciolacustrine deposits on its former floor. During early stages of downcutting, river-channel gravels capped by finer-grained floodplain and pond sediments were deposited as high as 20 m above modern river level. During full interglacials, the river continued to downcut, reaching positions at or a few meters below its modern level. Present-day bluff exposures along the Noatak River and its principal tributaries provide a record of glacial advances, lake stages, and alluvial episodes that span several glacial-interglacial cycles.

The river bluff designated Nk-37 is situated near the western end of the Noatak basin, well within the limits of Wisconsinan glaciation (Fig. 2). This unusually large cutbank exposure stands as high as 57 m and extends along the Noatak River for more than a kilometer. An apparent recessional moraine of the Anisak drift complex (Hamilton, 2001), which crosses the valley center here, caused the Noatak to be deflected northward into the unconsolidated deposits that underlie the north flank of its valley and to erode deeply into them.

The eastern part of Nk-37 contains two probable tills overlain by a largely concealed, thick sequence of glaciolacustrine and lacustrine sediments capped by loess; the western part of the bluff contains a higher-standing pair of diamicts overlain by thinner silt and peat (Fig. 3). These depositional sequences have been described by Hamilton (2001). The central part of the bluff, which is mostly concealed by massive slumps and flows, contains a wedge-like body of sediment that tapers westward and probably formed as a debris apron at the face of an ancient river bluff. This portion of Nk-37 is the focus of the present study.

Methods

FIELD METHODS

One of us (T. D. H.) mapped the overall stratigraphy of Nk-37 in 1983 and 1993 from a series of measured sections where gullies either allowed access to near-vertical parts of the bluff face or provided erosional "windows" into sectors blanketed by debris flows. Heights were measured by digital altimeter checked periodically by hand leveling; thicknesses of smaller units were measured by tape to the nearest centimeter. Stratigraphic relations between the vertical sections were determined by eye from the base of the bluff and confirmed by panoramic photographs taken from the point bar across the river from the cutbank. The exhumed bluff face and colluvial wedge in the central part of the bluff were surveyed in greater detail by T. D. H. and A. P. K. in 1995 (see Fig. 4). They measured and marked a baseline along the river edge, photographed this sector of the bluff at 25-m intervals, and measured vertical sections from

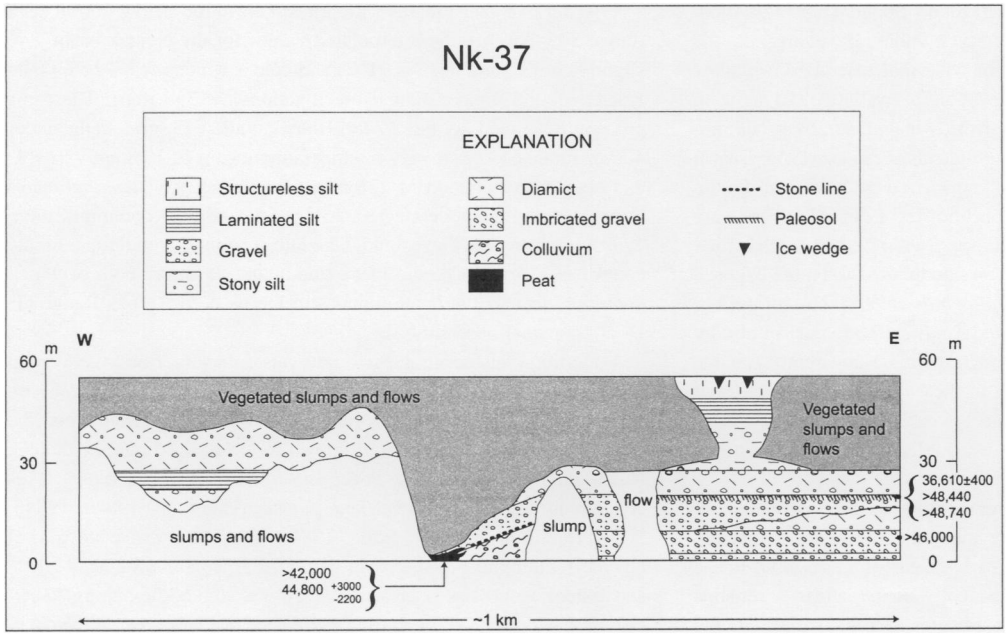

FIGURE 3. Overview of face of Nk-37, showing locations of radiocarbon samples and relationship of debris fan (bluff center) to sediments exposed farther west and east. See Table 1 for details on radiocarbon samples and analyses. Modified from Hamilton (2001).

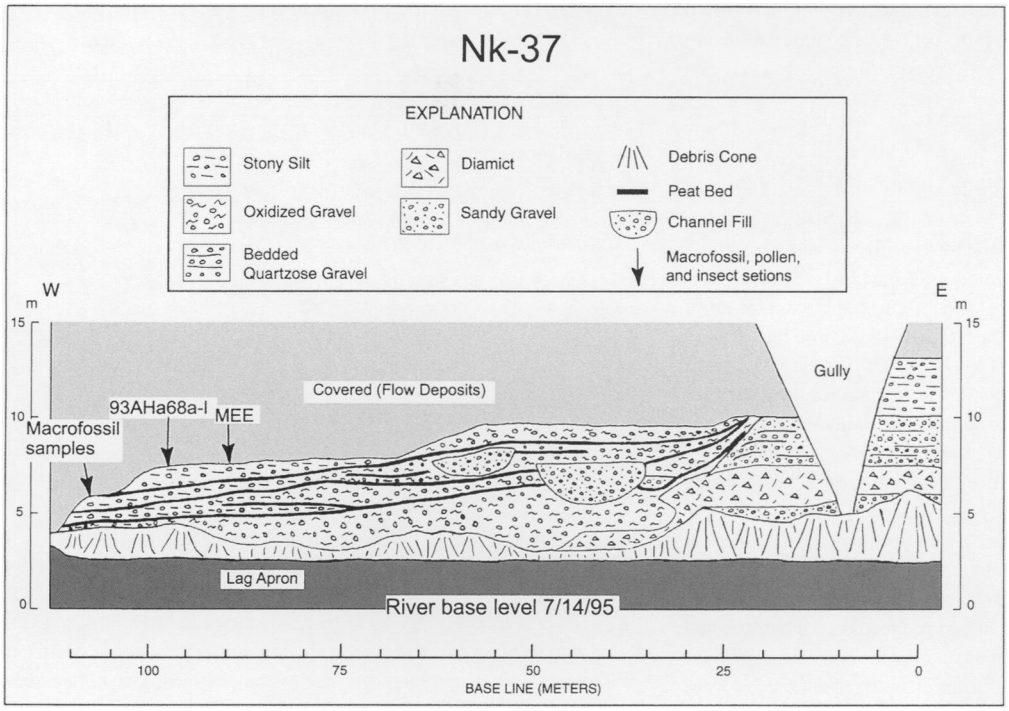

FIGURE 4. Detail of the debris fan at Nk-37 showing location of profiles from which pollen and macrofossil samples were collected. Mapped by T. D. Hamilton and A. P. Krumhardt, 1995.

designated positions along the baseline. Samples were located to the nearest 0.5 m on the baseline and to the nearest centimeter vertically.

POLLEN AND MACROFOSSILS

Two sections through the floodplain sequence were analyzed for pollen: 93Aha068 (11 samples, collected 1993) and MEE2 (13 samples, collected 1995); a further section was analyzed for macrofossils (collected 2000). Figures 4 and 5 indicate the locations and stratigraphic relationships of the sections; all three are within 20 m horizontally. Pollen was processed using conventional techniques and sodium polytungstate flotation (see Elias et al., 1999a, for details). Samples were counted to 300 grains where possible; when pollen concentrations were extremely low, counts were at least 100. Percentages were calculated from the sum of terrestrial pollen; aquatic taxa and spores were excluded from the sum. Pollen data were transformed and plotted using the programs Tilia and TiliaGraph, written by E. C. Grimm. Both detrended correspondense analysis (DCA) ordination and squared-chord distance comparisons of fossil and modern samples were attempted, but small sample numbers in both data sets precluded a meaningful quantitative comparison (modern Noatak pollen data are reported in Elias et al., 1999a).

After collection in the field, macrofossil samples were placed in plastic bags and stored at 0°C. Subsamples were measured volumetrically (30–60 mL), disaggregated with 2% KOH or 5% sodium pyrophospate, and screened through a 125-µm sieve. The portion caught in the sieve was examined under a Zeiss dissecting microscope at 12×–20×. Identifications were based on comparison with specimens housed at the University of Alaska–Fairbanks paleoecology laboratory and at the University of Alaska Museum herbarium. Seed atlases were also consulted, especially Anderberg (1994), Berggren (1969, 1981), Hurd et al. (1998), Katz et al. (1965),

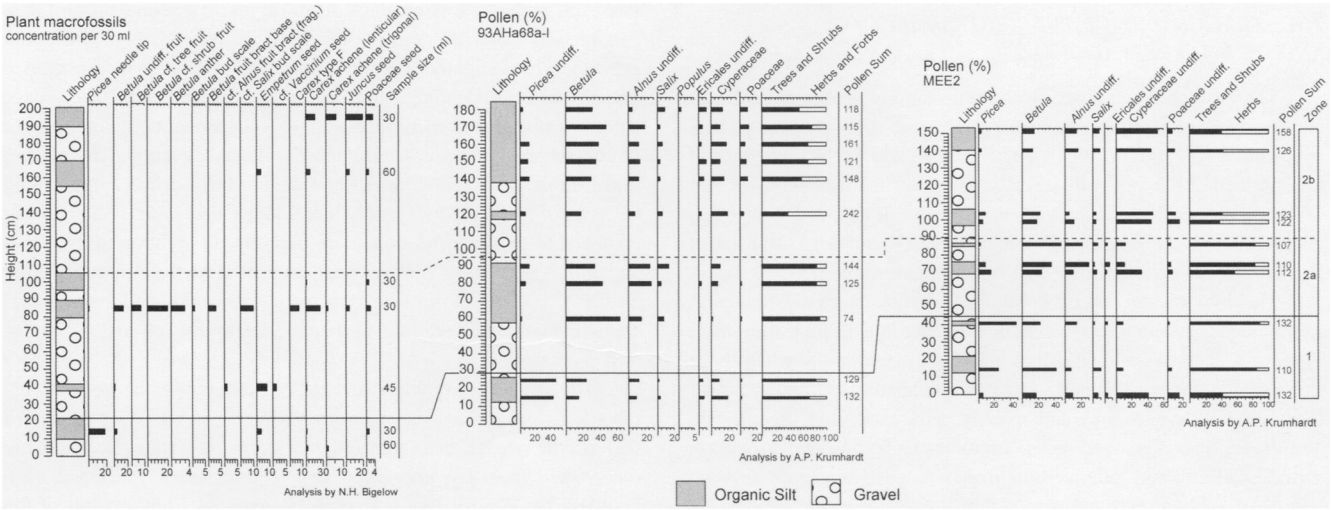

FIGURE 5. Fossil pollen and macrofossil stratigraphy of the debris fan, Nk-37. A tentative zonation is indicated, based on the stratigraphy and biostratigraphy of the three sections.

and Martin and Barkley (2000). After identification, the macrofossil data were converted to concentration per unit volume, allowing comparison between samples of varying volumes.

ENTOMOLOGICAL METHODS

Five bulk samples were taken for fossil insect analysis: 2 in 1994 from section 94Aha and 3 in 1995 from section MEE-2. Section 94AHa is located adjacent to 93Aha68a-l (see Figs. 4 and 5). Sample 025-SAE was taken from the uppermost peat (ca. 140–180) and 026-SAE from the third peat down (ca. 60–90 cm). The samples from MEE-2 came from the lowermost peat (0.13–0.22 m), the peat at 97–106 cm, the uppermost peat (140–153 cm). The samples were wet-screened over a 300-μm sieve to isolate organic residues. Extraction of insect fossils from organic detritus followed standard kerosene flotation methods (Elias, 1994). Specimens were sorted in 95% ethanol under low-power stereobinocular microscope. Most insect fossil specimens were stored in vials of 95% ethanol. Some were mounted on micropaleontological cards with gum tragacanth, a water-soluble glue. Identification of specimens was made by comparison with identified fossil and modern material in Elias's Alaskan collection, and by comparison with modern specimens in the Canadian National Collection, Agriculture Canada, Ottawa.

Paleoclimate estimates based on insect fossil assemblages were made using the Mutual Climatic Range (MCR) method (Atkinson et al., 1986). The MCR technique assumes that if the present climatic tolerance range of a beetle species is known, then fossil occurrences of that species imply a paleoclimate that was within the same tolerance range. To determine the climatic tolerances of the species in the fossil assemblages, we developed a climate envelope for each predatory and scavenging species in the fossil assemblages, based on the mean July and mean January temperatures of all the North American locations where the species presently occur. The 25-km gridded North American climate database (K. Anderson and others, unpublished data referred to previously) was used to pair climate parameters with the modern beetle-collection sites, using the grid location corresponding to each collecting site. We focused on predators and scavengers, as these groups are assumed to show the most rapid response to climate change. We calibrated the MCR results, using linear regression equations developed from modern beetle data sets for Alaska and the Yukon Territory (Elias et al., 1999b).

Results

THE STRATIGRAPHY OF THE CENTRAL SECTION AND ITS INTERPRETATION

The base of the exposed, westward-thinning wedge of sediment consists predominantly of indurated gravel that supports near-vertical exposures 6–10 m high (Fig. 4). The gravel generally is unsorted and nonstratified; its upper 4.0–4.5 m is oxidized reddish yellow (5YR 6/8). Its composition is nearly identical to the imbricated gravel that occurs through the eastern part of the bluff (Hamilton, 2001), but it lacks the fabric, bedding, and other fluvial structures of that clastic unit.

The thick eastern part of the wedge is dominated by subangular to subrounded clasts up to very small boulder size in beds up to 1 m thick. These gravel units are matrix-free in some places but elsewhere have a compact, silty sand matrix; they are interstratified with thinner (5–10 cm) beds of stony sand; pebbly, silty sand; and organic silt. The gravel fines westward, but it continues to be unsorted to weakly sorted, oxidized, and indurated; its matrix ranges from sandy to silty. Lenses of pebbles, silt, and peat within this sector of the deposit dip westward at 7–10°. Farther west, beds of stony sand and oxidized gravel 10–50 cm thick are interbedded with thinner (10–15 cm) beds of woody peat and organic silt. Strongly jointed dark gray (10YR 4/1) silt with pebble dropstones is present locally near the west end of the wedge.

TABLE 1

Radiocarbon ages for samples taken from Nk-37

Lab no.	^{14}C age	Material dated
Distal part of debris wedge		
USGS-1846	33,690 ± 300	*Picea/Larix* wood
USGS-3408	44,800 + 3000 −2000	Silty peat
USGS-3407	>42,000	*Salix* wood
East sector of bluff, floodplain deposit directly below upper diamict		
USGS-3287	36,610 ± 400	Peat
Beta-156895	>48,440	Wood
Beta-156896	>48,740	Wood fragments in compact peat
East sector of bluff, imbricated gravel		
USGS-1845	>46,000	*Picea/Larix* wood

The peat contains logs up to 10-cm diameter of *Picea* or *Larix* (U.S. Department of Agriculture, Forest Products Laboratory, Madison, Wisconsin, written communication, November 1983). Two radiocarbon ages on the logs are >42,000 yr B.P.; a third radiocarbon determination of 33,690 ± 300 yr B.P. is inconsistent with the others and probably incorrect (Table 1, and see below).

The lowest unit of the gravel forms a massive debris apron that is as much as 3.5 m thick near its east end but tapers westward to an exposed thickness of less than 0.5 m (Fig. 4). Younger gravel units, which are draped over the wedge, are separated by peat horizons and truncated by lenticular channel fillings of water-washed gravel. The peat beds generally are assignable to three horizons that form continuous unconformities through the debris wedge. The wedge terminates eastward against bedded gravel and nonstratified diamict that extend through the eastern part of the bluff. At contacts with the debris wedge, the diamict has been deformed by flowage and the gravel by downwarping.

Sediments overlying the wedge are generally obscured by flowage, but alluvial gravel with a stone line at its base appeared to overlap the eastern part of the wedge when Nk-37 was examined in 1983. This relationship was later obscured by debris flows.

The wedge of sediments is interpreted to be a debris apron that formed at the base of an ancient river-cut bluff. The apron and bluff face were buried by as much as 50 m of younger sediments and then exhumed by Holocene river erosion. Near its east end, the debris apron appears to be a slightly deformed and mixed variant of the imbricated gravel that occurs through the eastern part of the bluff. The wedge tapers westward and incorporates increasing amounts of fine-grained fluvial sediments and organic deposits in that direction. The coarser gravel in the wedge resembles deposits that form debris aprons along the base of the bluff today; the finer and more organic sediments are comparable to Holocene floodplain deposits. In addition, the diamict and imbricated gravel units, where truncated at the inferred former bluff face, exhibit deformation structures that would result from loss of support due to undercutting by lateral stream erosion at the base of a river bluff.

The ancient river bluff and debris apron link the depositional records of the eastern and western segments of Nk-37. The eastern part of the wedge is dominated by sediments that were probably redeposited from the imbricated gravel unit, and it is capped by a bouldery lag deposit that was probably derived from erosion of the strongly oxidized lower diamict, which overlies the gravel. Above the lag deposit, the wedge is overlapped by fluvial gravel, which, farther

east, is oxidized to only 20 cm depth and contains floodplain deposits dated at 36,610 ± 400, >48,440, and >48,740 yr B.P. (Table 1). The two samples that yielded nonfinite ages were collected in 2000 under carefully controlled conditions and dated by accelerator mass spectrometry (AMS). We dated the peat contact as well as the wood to minimize the potential error from fluvial redeposition. The nonfinite ages we obtained for this floodplain horizon are compatible with nonfinite radiocarbon ages recently determined father west on ice dams that blocked the Noatak River during the Anisak advance (T. D. H., unpublished data). For these reasons, the apparently finite age of the remaining sample, which was reported in an earlier publication (Hamilton, 2001), is now considered invalid. The floodplain deposit is glaciotectonically deformed, confirming other identification criteria (Hamilton, 2001) that demonstrate the overlying diamict is glacial till. Glaciolacustrine stony silt and other fine-grained deposits overlie the diamict. The debris wedge therefore formed after deposition of the lower diamict but prior to the formation of the overlying gravel and its capping floodplain deposit.

Relations of the debris apron to deposits farther west are less directly visible, but the apron almost certainly is overlain by both diamicts exposed in the western part of the bluff and by the unweathered, inorganic laminated sediments that separate them. The upper diamict has ridge-like relief, especially at its east end, and its lateral equivalent in the eastern part of Nk-37 is glaciolacustrine silt with abundant dropstones. These deposits probably represent the end moraine of the late Anisak readvance, which crosses the Noatak valley here, and an associated proglacial lake. Because the upper and lower diamicts in the western part of the bluff are separated only by inorganic sand and silt beds that contain probable flow-till and turbidite deposits (Hamilton, 2001), only a brief interval of time must have separated those diamicts. The lower diamict therefore must also be of Anisak age. This diamict is probably correlative with the upper diamict of the eastern section of Nk-37, which occurs at the same height and overlies gravel with a shallow weathering profile that probably reflects an interstadial age.

The fossil bluff face and debris apron are thus clearly older than slightly oxidized interstadial alluvium related to the Anisak glaciation of Wisconsinan age and the generally unweathered sediments that overlie it. In contrast, all deposits older than the bluff and its debris apron are oxidized throughout, ranging from moderately to strongly oxidized with increasing age. These relationships suggest that a last interglacial (MIS-5) age for the exhumed bluff and debris apron is likely, but an older interglacial age is not precluded.

BIOTIC DATA FROM THE DEBRIS-FAN DEPOSIT

Plant fossil samples came from the three main organic beds within the debris fan (Fig. 5). Additional pollen samples came from organic stringers within gravel between the main organic beds. Fossil pollen was quite sparse, and some samples proved difficult to count. Both pollen sequences (Fig. 5) contain *Picea* (5–40%), *Betula* (20–40%), and *Alnus* (5–30%). *Salix*, Cyperaceae, Poaceae, *Sphagnum*, and Ericales are consistently present. In both sequences, *Picea* values are generally highest in the basal half of the section. *Betula* and *Alnus* pollen dominate the middle peat. Spectra from the upper peat are dominated by Cyperaceae and forbs, and *Picea* pollen values are lower (ca. 10% or less).

In the macrofossil sequence (Fig. 5), *Picea* needles occur with most abundance in the lowermost peat; they are present in the middle peat but absent from the upper peat. A few *Betula* fruits occurred in the lower peat, more occurred in the middle peat, and none were found in the upper peat. Based on fruit shape and size (see Van Dinter and Birks, 1996), some *Betula* fruits have been tentatively identified as tree birch. However, confirmation was not possible because fruit wings were absent. Macrofossils of *Carex*, grasses, and herbs are more abundant in the middle and particularly in the upper peat.

In quantitative comparisons of the fossil and modern samples, pollen samples from the lower part of both sections were most similar to modern gallery forest samples, but the results were statistically weak and are not reported here. However, the macrofossil evidence of spruce needles confirms that these fossil samples indicate the local presence of *Picea*. Furthermore, *Picea* pollen of 10% or more typically indicates forested or tree-line conditions (Anderson and Brubaker, 1986; Elias et al., 1999a).

One fossil insect sample was taken from near the base of the fan and 2 each from peat beds located in the middle and upper portions of the fan (Fig. 4, Table 3). The insect faunal assemblages include 32 taxa in 11 families of beetles (Coleoptera) and ants (Hymenoptera, Formicidae; Table 2). Four of the 5 fossil assemblages contained sufficient numbers of species to allow an MCR estimation (the omitted sample came from the middle peat). Samples and calibrated MCR estimates are listed in Table 3.

The sample from the organic subunit near the base of section MEE-2 (0.13–0.22 m) contains sparse insect remains, and no indicators of forest are present. The assemblage from the middle organic subunit of MEE-2 (97–106 cm) comprises a mixture of tundra and forest-dwelling species, the latter including *Carphacis nepigonensis*, a rove beetle found today in the boreal regions of Canada (Campbell, 1980). No bark beetles or other obligate tree-associated insects were found in this assemblage. The sample from the uppermost subunit of MEE-2 (140–153 cm) produced by the far the richest fossil insect assemblage. This sample contained a number of spruce bark beetles and other tree-associated insects, including a carpenter ant that nests in rotting logs. The spectra from 94AHa-25 (120 cm) and 94Aha-26 (45 cm) had lower abundances and were less diverse than their MEE-2 counterparts (see Table 2).

The MCR estimates of mean July temperature range from 10.7 to 13.4°C and the estimates of mean January temperature from –21.3 to –25.0°C.

Discussion

PALEOECOLOGICAL RECONSTRUCTION

The fan and floodplain deposits likely represent hundreds, maybe thousands, of years, and the record is likely to provide a relatively short temporal window upon the interglacial environment. In such a depositional setting, although there may be a fluvial transport component, much of the pollen and other fossil material probably originated locally (Edwards, 1997), and is therefore likely to reflect local rather than regional changes. The stratigraphic data and paleo–river level suggest that the biotic remains come from interglacial deposits. Pollen of *Picea*, *Betula*, and *Alnus* throughout the sections confirms the interglacial character of the deposits.

The record shows local changes with time. *Picea* values of 20–60% in the basal peat beds, plus the fossil spruce needles, argue strongly for the presence of spruce forest while the lower floodplain sediments were being deposited on the fan. *Picea* pollen is present at values of up to ca. 10% in the pollen spectra from the middle and upper peat bands, suggesting spruce was still in the vicinity, while declining abundances of needles indicate it may have later become scarce or absent locally. Its removal from the immediate locality may have been due to geomorphic and/or successional changes related to channel dynamics. The macrofossils in the upper part of the section suggest moist, sedge-dominated vegetation at the site. The pollen spectra also show increasing abundance of sedge, but the continuing abundance of *Betula*, *Alnus*, and *Salix* and the presence of *Picea* pollen in values up to 10% suggest that shrub-tundra and some spruce forest occupied surrounding areas.

TABLE 2

Taxonomic list of insects identified from Nk-37 fossil assemblages, in minimum number of individuals per assemblage

Taxon	Sample				
	AHa 94-25	AHa 94-26	MEE2 13–22 cm	MEE2 97–106 cm	MEE2 140–153 cm
COLEOPTERA					
Carabidae					
Diacheila polita (Fald.)	1	—	1	1	—
Bembidion grapii Gyll.	—	—	—	1	—
Bembidion sulcipenne hyperboroides Lth.	—	—	1		1
Bembidion spp.					3
Stereocerus haematopus (Dej.)				1	
Pterostichus brevicornis (Kby.)				1	2
Pterostichus pinguedineus (Eschz.)					1
Pterostichus similis Mann.					2
Pterostichus (Cryobius) spp.	1	1	1	2	6
Agonum consimile (Gyll.)					1
Agonum sp.					2
Hydrophilidae					
Helophorus sempervarians Angus	1				
Hydrobius fuscipes (L.)					1
Staphylinidae					
Arpedium brachypterum (Grav.)					1
Lathrobium spp.	1		1		2
Stenus spp.	1	1	1	1	6
Carphacis nepigonensis (Bernh.)				1	
Tachyporus nimbicola Campbl.					2
Tachinus brevipennis Sahlb.	2		2	1	
Gymnusa atra Csy.					1
Aleocharinae genus et sp. indet.				3	4
Silphidae					
Silpha trituberculata Kby.					1
Leptodiridae					
Catops beringiensis Peck					1
Scarabaeidae					
Serica sp.					1
Byrrhidae					
Byrrhus sp.		1			
Chrysomelidae					
Plateumaris sp.					1
Curculionidae					
Lepidophorus lineaticollis Kby.		1			
Lepidophorus inquinatus (Mann.)					2
Scolytidae					
Polygraphus rufipennis Kby.					2
Ips sp.					1
Phloeotribus lecontei Schedl.					4
HYMENOPTERA					
Formicidae					
Camponotus herculeanus (L.)					3

Supporting evidence of forest on the floodplain comes from small logs of conifer wood of infinite radiocarbon age observed in this unit farther upstream in the section and from the obligate forest insects: bark beetles and the carpenter ant suggest that well-established forest, which included spruce, existed in the area as the upper sediments were being laid down. *Populus* pollen (which is typically underrepresented compared with *Picea* or *Betula*) in the uppermost sample of 93Aha68 indicates the presence of poplar locally. Tree birch may have been present, according to the tentative identification on some fossil birch fruits. Thus, the composite fossil data suggest that spruce forest, with some poplar and possibly tree birch, occurred in the floodplain at NK-37 throughout the period represented by the fossil record. The spruce may have been restricted to gallery forest, similar to that found today on the lower Noatak, or it may have been part of more widespread forest cover in the Noatak basin—the data do not allow us to distinguish between these possibilities.

The MCR July temperature estimates range from 10.7 to 13.4°C (modern interpolated values: ca. 11.0°C) and the January estimates from −21.3 to −25.0°C (interpolated: ca. −24.0°C). The variation in estimates likely reflects the low diversity of three of the four samples.

TABLE 3

Temperature estimates for the NK-37 interglacial deposits from the beetle-based MCR method

Sample and height above base of fan (samples in order of increasing height above datum)	T_{max}(°C)	T_{min} estimate (°C)
MEE2 0.13–0.22 m	11.3	−23.5
94 AHa-26-SAE (0.45 m)		
MEE2 0.97–1.06 m	13.4	−21.3
MEE2 140–153 m	12.4	−25
94 AHa-25-SAE (1.2 m above base)	10.4	−24.1

Sample MEE2 140–153 cm is by far the most diverse and provides estimates of 12.4 and −25.0°C (Table 3). We conclude that the Nk-37 area likely experienced temperatures slightly greater than modern in summer and similar to modern in winter.

IMPLICATIONS OF THE DATA

Tree-line response to MIS-5 climates is of interest because MIS-5e (and possibly other substages) appears to have been warmer than the Holocene and is thus an analogue for global warming. As mentioned above, it is currently unclear how sensitive arctic tree line is to warming, yet the boreal forest response may be a potential source of major feedback to the climate system. Controls over the latitudinal limits of the boreal forest vary, depending upon spatial scale, and near the limits of spruce distribution today, factors other than climate can be dominant, for example, local topography and geomorphology, dispersal, and disturbances such as fire.

Continental-scale climate features such as the mean position of the arctic front, monsoonal flows between the oceans and continental interiors, and Milankovitch-type insolation-driven warming of continental areas appear to have driven asynchronous displacements of the Holocene circumpolar tree-line (e.g., Ritchie et al., 1983; MacDonald et al., 1993; MacDonald et al., 2000). Ecological constraints related to dispersal ability, preexisting vegetation conditions (Ritchie, 1984, 1986), or modification of regional climatic patterns by local topography and substrate conditions dampen or enhance a response to a regional climate change (Timoney, 1995; Rowland, 1996). Near its climatic limits in particular, spruce may occur as part of a vegetation mosaic, with topography, soil, floodplain dynamics, and/or fire exercising strong control over local tree distribution (Lavoie and Payette, 1996; Landhausser and Wein, 1993). In such cases, tree line may be relatively unresponsive to climate changes (e.g., Sirois and Payette, 1991; Arseneault and Payette, 1997a, 1997b; MacDonald et al., 1998).

For example, the presence of floodplain gallery forest in the lower Noatak, and its absence in the Noatak Basin, are not explained by differences in climatic means—at least those based upon the interpolated climate data set. Either other climate factors, such as winter wind damage or icing, differentiate these sites, or the distribution of spruce along the Noatak is controlled largely by nonclimatic factors. Rowland (1996) has shown that in the lower Noatak, the presence of spruce is strongly correlated with well-drained areas such as river bars, alluvial fans, ice-push margins, and morainal ridges, indicating that geomorphologic processes and substrate conditions exert a major control over tree distribution.

The vagaries of dispersal may also contribute to the intermittent occurrence of spruce near its climatic limits, even where the general climatic conditions and local substrates allow the growth of spruce (which appears to be the case in the Noatak Basin today). Since its arrival in northwest Alaska in the mid Holocene (Anderson, 1985), spruce has evidently exploited a dispersal route from the main body of the boreal forest via the mouth of the Noatak into the lower valley (Fig. 1). However, to disperse a further ca. 80 km upstream to the Noatak Basin, through a section of the river where the valley is deeply incised and there are few favorable establishment sites, poses a greater challenge. The alternative route into the basin is over the topographic and climatic barrier of the Baird Mountains via long-distance dispersal (Fig. 1), but dispersal along this route has not occurred during the Holocene.

When we consider the (assumed) interglacial extension of forest cover documented at Nk-37, it is difficult to know what significance to place on the data. Two explanations appear possible. One is that regional climatic conditions in the period represented by the record were little different from today and spruce became established as gallery forest in the Noatak Basin via a low-probability long-distance dispersal event. The other is that significantly better growing conditions made it much easier for spruce to become widely established in the Noatak Basin. In support of the latter explanation, the weight of the insect data suggests that summer temperatures in the basin may have been warmer than at the present time. Furthermore, at Squirrel Lake south of the Baird Mountains (Fig. 1), pollen data from MIS-5 indicate extensive (probably closed) forest where there is a mosaic of forest and tundra today (P. Anderson and P. Bartlein, personal communication, 1999). If the denser forest were reflected in higher tree limits, this would shorten the dispersal distance and effectively lower the elevation barrier between the Kobuk and Noatak drainages.

Given the potential impact of shifts in boreal forest distribution under global warming, there is a need to find further sites recording clearer arctic tree-line displacements in order to assess tree-line sensitivity to warming.

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